

Hunting for heavy composite Majorana neutrinos at the LHC

R. LEONARDI,^{1,2} L. ALUNNI,^{1,2} F. ROMEO,³ L. FANÒ,^{1,2} and O. PANELLA²

¹*Dipartimento di Fisica, Università degli Studi di Perugia, Via A. Pascoli, I-06123, Perugia, Italy*

²*Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Via A. Pascoli, I-06123 Perugia, Italy*

³*Institute of High Energy Physics, 19B Yuquan Lu, Shijingshan District, Beijing, 100049, China*

(Dated: December 22, 2015)

Motivated by the recent observation of an excess in the $eejj$ channel by the CMS collaboration we investigate the search for heavy Majorana neutrinos stemming from a composite model scenario at the upcoming LHC Run II at a center of mass energy of 13 TeV. While previous studies of the composite Majorana neutrino were focussed on gauge interactions via magnetic type transition coupling between ordinary and heavy fermions (with mass m^*) here we complement the composite model with contact interactions at the energy scale Λ and we find that the production cross sections are dominated by such contact interactions by roughly two/three orders of magnitude. This mechanism provides therefore very interesting rates at the prospected luminosities. We study the same sign di-lepton and di-jet signature ($pp \rightarrow \ell\ell jj$) and we discuss how it can account for the excess in the $eejj$ invariant mass distribution, and perform a fast detector simulation based on DELPHES. We compute 3σ and 5σ contour plots of the statistical significance in the parameter space (Λ, m^*) . We find that the potentially excluded regions at $\sqrt{s} = 13$ TeV are quite larger than those excluded so far at Run I considering searches with other signatures.

PACS numbers: 12.60.Rc; 14.60.St; 14.80.-j

I. INTRODUCTION

The recent discovery [1, 2] of the Higgs boson at the CERN Large Hadron Collider (LHC) has certainly crowned in the most spectacular way an almost half-century long history of successes of the standard theory of the electroweak interactions, the so called standard model (SM).

Albeit the tremendous efforts put in by the experimental collaborations working in the LHC experiments the hunt for new physics (supersymmetry, compositeness, extra dimensions etc..) has been so far unsuccessful. Impressive and increasingly higher new bounds on the scale of several beyond the standard model (BSM) scenarios are continually being updated.

However the CMS Collaboration has recently reported an excess over the SM background expectations in the $eejj$ and $e\cancel{p}_Tjj$ final states where \cancel{p}_T is the missing transverse energy. The analysis in [3] for a search of right-handed gauge boson, W_R , based on 19.7 fb^{-1} of integrated luminosity collected at a center of mass energy of 8 TeV reports a 2.8σ excess in the $eejj$ invariant mass distribution in the interval $1.8 \text{ TeV} < M_{eejj} < 2.2 \text{ TeV}$. A CMS search [4] for first generation lepto-quarks at a center of mass energy of 8 TeV and 19.6 fb^{-1} of integrated luminosity reported an excess of respectively 2.4σ and 2.6σ in the $eejj$ and $e\cancel{p}_Tjj$ channels respectively.

Several attempts have been proposed in the literature to explain the above CMS excesses in the context of various standard model extensions. For instance in [5, 6] the authors propose an explanation of the excesses in the context of W_R decay by embedding the conventional LRSM ($g_L \neq g_R$) in the $SO(10)$ gauge group. Studies of the $eejj$ excess in the context of W_R and Z' gauge boson and heavy neutrinos (N) –coupling mainly to electrons–

production and decay appear in [7–9]. Similarly [10] discusses a model with pseudo-Dirac heavy neutrinos providing a fit to all excesses in a generic LRSM with arbitrary g_R , W - W_R boson mixing, heavy neutrino mass N and the ν - N mixing. In addition, the authors point we point out the consequences of the excesses for neutrinoless double beta decay $0\nu\beta\beta$ decay, and find for example that $0\nu\beta\beta$ actually provides a pretty severe limit on the ν - N mixing assuming the excesses are real.

Other interpretations have been proposed within the context of models with vector-like leptons as in [11] showing that resonant pair production of such vector-like leptons decaying to an electron and two jets leads to kinematic distributions consistent with the observed CMS data. The $eejj$ excess has been shown to arise as well in R -parity violating models through spton resonant production [12–14]. An alternative scenario based on lepto-quarks is proposed in [15, 16], discussing also possible connections to dark matter, which fits the data of the excess seen by CMS. In [17] the observed CMS excesses are explained within superstring inspired E_6 models which can also accomodate for the baryon asymmetry of the universe via lepto-genesis. Other studies have emphasized that the observed differences between the $eejj$, $\mu\mu jj$, same sign (SS) and opposite sign (OS) channels and could be addressed including mixing and CP phases of the heavy neutrinos [18]. On the other hand it is well known that the like-sign di-lepton and di-jet ($eejj$), $\Delta L = 2$ violating final state (Keung-Senjanovic process), is the golden signature to look for heavy Majorana neutrinos at high energy hadron collisions [19–28]. Studies of heavy (pseudo-Dirac) neutrino production at the LHC within the inverse see-saw mechanism have been performed [29], also considering the quark-gluon fusion mechanism [30, 31].

In this paper, assuming the existence of a heavy Majorana neutrino arising from the well known scenario of compositeness of quarks and leptons, complemented with contact interactions, we propose to study the $eejj$ signature and show that the model in its simplest version can reproduce the essential features of the observed excess in the $eejj$ invariant mass distribution. We discuss how, with some refinement, it has the potential to address also other aspects of the excess, such as the absence of a peak in the second-leading-electron $-jj$ invariant mass distribution, the charge asymmetry of the excess and the fact that the same excess is not observed in the $\mu\mu jj$ channel [3].

In this scenario the heavy excited states (q^*, e^*, ν^*) couple, through gauge interactions, with the ordinary SM fermions via magnetic type couplings. Current bounds on excited lepton masses (generically indicated by m^*) have been recently strengthened by the LHC Run I analyses [32, 33] of the $\ell\ell\gamma$ signature arising from ℓ^* production ($pp \rightarrow \ell\ell^*$), via four fermion contact interactions with a compositeness scale Λ , followed by the decay $\ell^* \rightarrow \ell\gamma$. In particular in [32] the ATLAS Collaboration reporting an analysis at $\sqrt{s} = 8$ TeV with an integrated luminosity of 13 fb^{-1} give a lower bound on the mass of the excited leptons $m^* > 2.2$ TeV (derived within the hypothesis $m^* = \Lambda$). In [33] the CMS Collaboration reported the results of data collected with 19.7 fb^{-1} at $\sqrt{s} = 8$ TeV and (always assuming $m^* = \Lambda$) excluded excited electron (muon) masses up to 2.45 (2.48) TeV. Preliminary studies within the compositeness scenario of the like-sign di-lepton and di-jet signature were performed long ago [22], assuming the excited neutrino $\nu^* = N$ to be a Majorana particle. Here our aim is to complement the composite Majorana neutrino model of ref. [22] with contact interactions which are again a generic expectation of a composite fermion scenario [34]. Based on previous studies related to the production at LHC of exotic doubly charged leptons [35] we expect these contact interactions to be the dominant mechanism for the resonant production of the heavy Majorana neutral particles N in the process $pp \rightarrow \ell N$. This expectation is indeed verified by our numerical simulations performed with a custom version of CalcHEP [36, 37] where our model has been implemented. The heavy Majorana neutrino is produced resonantly in association with a lepton ($pp \rightarrow \ell N$) and then given the relatively important branching ratio for the decay $N \rightarrow \ell jj$ we perform a detailed kinematic study of the like-sign di-lepton and di-jet final state:

$$pp \rightarrow \ell jj \quad (1)$$

including the relevant standard model backgrounds.

Our study shows clearly that a full fledged analysis of the upcoming data from the Run II of LHC at $\sqrt{s} = 13$ TeV has the potential of observing the signature or alternatively excluding larger portions of the model parameter space compared to those already excluded from analyses of Run I [32, 33].

The rest of the paper is organized as follows: In Sec. II

we review the theoretical composite model; in Sec. III we discuss the heavy neutrino production cross sections and decay rates; in Sec. IV we discuss the same-sign dilepton and di-jet signature and the main associated SM backgrounds; in Sec. V we present the results of the fast simulation obtained through the DELPHES [38] software; finally Sec. VI gives the conclusions with outlooks.

II. COMPOSITE MODEL(S) WITH GAUGE AND CONTACT INTERACTIONS

In this section we review the composite model of excited fermions investigated in [22] within the hypothesis of a heavy Majorana neutrino. Compositeness of ordinary fermions is one possible scenario beyond the standard model. In this approach quarks and leptons are assumed to have an internal substructure which should become manifest at some sufficiently high energy scale, the compositeness scale Λ . Ordinary fermions are then thought to be bound states of some as yet unobserved fundamental constituents generically referred to as *preons*. While building a fully consistent composite theory has proven to be quite difficult some important and model independent features of the compositeness scenario can be phenomenologically addressed. Quite natural properties of this picture are [39–41]: (i) the existence of excited states of such low lying bound states of preons $q^*, e^*, \nu^* \dots$ with masses $m^* \leq \Lambda$; and (ii) contact interactions between ordinary fermions and also between ordinary and excited fermions. Let us consider here the various possible composite models with respect to the idea of introducing lepton number violation (LNV) via a composite Majorana neutrino.

(a) Homo-doublet model.

The homo-doublet model [42, 43] contains a left handed excited doublet along with a right handed excited doublet:

$$L_L^* = \begin{pmatrix} \nu_L^* \\ e_L^* \end{pmatrix}, \quad L_R^* = \begin{pmatrix} \nu_R^* \\ e_R^* \end{pmatrix}. \quad (2)$$

Typically the left and right handed doublet are assumed to have the same mass. It is known that two left and right Majorana fields with the same mass combine to give a Dirac field (with a Dirac mass) [44]. The homo-doublet model, as laid out, cannot therefore accommodate Majorana excited neutrinos, and hence lepton number violation (LNV). This becomes possible if one is willing to introduce a mass difference between the left and right doublet ($\nu_L^* - \nu_R^*$ mixing) or, in other words, a breaking of the L-R symmetry. Such a possibility has been discussed for instance in ref. [45] where the ν^* is possibly a linear combination (with mixing coefficients) of Majorana mass eigenstates.

On the other end, if we do not want to introduce a mass splitting (or mixing) between the left and right components in the homo-doublet model, we can account for

LNV advocating different models within the compositeness scenario which naturally can accommodate a Majorana neutrino [45, 46]. These are the following:

(b) Sequential type Model.

The sequential model contains excited states whose left handed components are accommodated in $SU(2)$ doublets while the right handed components are $SU(2)$ singlets:

$$L_L^* = \begin{pmatrix} \nu_L^* \\ e_L^* \end{pmatrix}; \quad e_R^*, \quad [\nu_R^*]; \quad (3)$$

and the notation $[\nu_R^*]$ means that ν_R^* is necessary if the excited neutrino is a Dirac particle while it could be absent for a Majorana excited neutrino. The magnetic type interactions in this case can be constructed by coupling the left-handed excited doublet to the SM fermion singlets via the Higgs doublet [45]. This results in interaction couplings suppressed by a factor v/Λ [46] where $v \approx 246$ GeV is $\sqrt{2}$ times the vacuum expectation value of the Higgs field.

(c) Mirror type Model.

It is assumed to contain a right handed doublet and left handed singlets:

$$e_L^*, \quad [\nu_L^*]; \quad L_R^* = \begin{pmatrix} \nu_R^* \\ e_R^* \end{pmatrix}, \quad (4)$$

where we may assume that there is no left handed excited neutrino (ν_L^*) so that we can associate to ν_R^* a Majorana mass term and ν^* is a Majorana particle. This model is described by a magnetic type coupling between the left-handed SM doublet and the right-handed excited doublet via the $SU(2)_L \times U(1)_Y$ gauge fields [45, 46]:

$$\mathcal{L} = \frac{1}{2\Lambda} \bar{L}_R^* \sigma^{\mu\nu} \left(g f \frac{\boldsymbol{\tau}}{2} \cdot \mathbf{W}_{\mu\nu} + g' f' Y B_{\mu\nu} \right) L_L + h.c., \quad (5)$$

where $L^T = (\nu_{\ell L}, \ell_L)$ is the ordinary $SU(2)_L$ lepton doublet, g and g' are the $SU(2)_L$ and $U(1)_Y$ gauge couplings and $\mathbf{W}_{\mu\nu}$, $B_{\mu\nu}$ are the field strength for the $SU(2)_L$ and $U(1)_Y$ gauge fields; f and f' are dimensionless couplings which are typically assumed to be of order unity.

The relevant charged current (gauge) interaction of the excited Majorana neutrino $N = \nu^*$ is then:

$$\mathcal{L}_G = \frac{gf}{\sqrt{2}\Lambda} \bar{N} \sigma_{\mu\nu} \ell_L \partial^\nu W^\mu + h.c. \quad (6)$$

The above mirror type model is therefore the model to which we will refer our detailed simulation of the like sign di-lepton signature at the Run II of the LHC.

Incidentally we note that SM extensions involving mirror fermions have been recently considered [47] with respect to the phenomenology of the production of mirror quarks at the LHC.

At last we may add that one could also consider extended isospin composite models [48] where the excited states are grouped in triplets ($I_W = 1$) or quadruplets ($I_W = 3/2$) instead of doublets ($I_W = 1/2$) as considered above. Such extensions of the composite scenario

contain exotic charge states like doubly charged leptons and quarks of charge $Q = (5/3)e$. Some phenomenology of these extensions relative to the doubly charged leptons has been addressed recently [35, 49]. Such extended weak isospin composite models could also be considered with the additional hypothesis that the excited neutrino is a Majorana particle.

The model with $I_W = 1$ can only couple [48] the triplet $\epsilon^T = (L^0, L^-, L^{--})$ with the right-handed lepton singlet ℓ_R . Therefore we may assume a sequential type structure with a left-handed triplet and right-handed singlets. If the L_R^0 is missing we may assume for the L_L^0 a Majorana mass term and so the excited neutral L^0 of the triplet is a Majorana neutrino (N). The magnetic type interaction reads:

$$\mathcal{L} = \frac{f_1}{\Lambda} \bar{\epsilon}_L \sigma_{\mu\nu} \ell_R \partial^\nu W^\mu + h.c. \quad (7)$$

where f_1 is an unknown dimensionless coupling in principle different from f appearing in Eqs. (5&6). The relevant charged current interaction of the neutral component of the triplet L^0 is in this case:

$$\mathcal{L} = \frac{f_1}{\Lambda} \bar{L}^0 \sigma_{\mu\nu} \ell_R \partial^\nu W^\mu + h.c. \quad (8)$$

which differs from the one in Eq. (6) in the chirality of the projection operator.

The $I_W = 3/2$ quadruplet $\epsilon^T = (L^+, L^0, L^-, L^{--})$ couples instead [48] with the left-handed SM doublet, so that assuming a mirror type scenario and that there is no L_L^0 we can assign to L_R^0 a Majorana mass term so that the L^0 neutral of the quadruplet can be a Majorana neutrino (N). The magnetic type interaction is [48]:

$$\mathcal{L} = C\left(\frac{3}{2}, M|1, m; \frac{1}{2}, m'\right) \frac{f_{3/2}}{\Lambda} (\bar{\epsilon}_R)_M \sigma_{\mu\nu} \ell_{Lm'} \partial^\nu W_m^\mu + h.c. \quad (9)$$

where $f_{3/2}$ is an unknown dimensionless coupling in principle different from f, f_1 and $C(\frac{3}{2}, M|1, m; \frac{1}{2}, m')$ are Clebsch-Gordan coefficients. In particular in the case of $I_W = 3/2$ the relevant neutrino charged current interaction turns out to have the same structure as in Eq. (6):

$$\mathcal{L} = \frac{f_{3/2}}{\sqrt{3}\Lambda} \bar{L}^0 \sigma_{\mu\nu} e_L \partial^\nu W^\mu + h.c. \quad (10)$$

Therefore the interaction in Eq. (6) effectively describes the charge current interaction of a heavy Majorana neutrino both in the ($I_W = 1/2$) mirror type model or in a composite model with extended weak isospin ($I_W = 3/2$), always of the mirror type, provided that we make the correspondence $\sqrt{2}f_{3/2}/\sqrt{3} = f$.

Contact interactions between ordinary fermions may arise by constituent exchange, if the fermions have common constituents, and/or by exchange of the binding quanta of the new unknown interaction whenever such binding quanta couple to the constituents of both particles [34, 46]. The dominant effect is expected to be given

by the dimension 6 four fermion interactions which scale with the inverse square of the compositeness scale Λ :

$$\mathcal{L}_{\text{CI}} = \frac{g_*^2}{\Lambda^2} \frac{1}{2} j^\mu j_\mu \quad (11a)$$

$$j_\mu = \eta_L \bar{f}_L \gamma_\mu f_L + \eta'_L \bar{f}_L^* \gamma_\mu f_L^* + \eta''_L \bar{f}_L^* \gamma_\mu f_L + h.c. \\ + (L \rightarrow R) \quad (11b)$$

where $g_*^2 = 4\pi$ and the η factors are usually set equal to unity. In this work the right-handed currents will be neglected for simplicity.

The single production $q\bar{q}' \rightarrow N\ell$ proceeds through flavour conserving but non-diagonal terms, in particular with currents like the third term in Eq. 11b which couple excited states with ordinary fermions:

$$\mathcal{L}_{\text{CI}} = \frac{g_*^2}{\Lambda^2} \bar{q}_L \gamma^\mu q'_L \bar{N}_L \gamma_\mu \ell_L. \quad (12)$$

which were not considered in [22, 49] while are now fully implemented in our simulations.

The gauge interactions in Eq. (6) and the contact interactions in Eq. (12) have been implemented in the CalcHEP [36, 37] generator. The Feynman rules corresponding to the lagrangians in Eqs. (6,12) have been derived with FeynRules [50] a Mathematica [51] package which allows to derive the Feynman rules of a given quantum field theory model once the lagrangian is given. In this study we have added the gauge interactions given in Eq. (6) and contact interactions in Eq. (12) taking into account the Majorana nature of the excited heavy neutrino N .

We conclude this section with one final remark regarding the assumption that in this work the dimensionless couplings $f, f', f_1, f_{3/2}$ are $\mathcal{O}(1)$. The production cross sections and the simulations presented in the following are obtained assuming $f = f' = f_1 = f_{3/2} = 1$. This should be recalled when quoting the resulting bounds on the other parameters of the model, namely (m^*, Λ) . At this regard we point out that our results cannot not be easily rescaled if $f = f', f_1, f_{3/2} \neq 1$ due to the presence of the contact interaction mechanism which does not depend explicitly on these constants. Although the production mechanism is dominated by contact interactions the gauge interactions do affect the decay of the heavy neutrinos. A direct comparison with other studies [52, 53] which derived bounds on the mixing parameters for the electron flavour of the heavy neutrinos is therefore not possible at the moment. Indeed our production cross sections cannot be simply rescaled because of the presence of the contact interaction production mechanism. We would need to implement in the generator a model with the additional parameters $f, f', f_1, f_{3/2}$.

III. CROSS SECTION AND DECAY WIDTH OF THE COMPOSITE MAJORANA NEUTRINO

Heavy Majorana neutrinos N can be singly produced in association with a lepton ℓ in pp collisions. The process

$pp \rightarrow N\ell$ can occur via both gauge (Fig. 1, first diagram in the right-hand side) and contact interactions (Fig. 1, second diagram in the right-hand side).

We now present here the production cross section for the heavy Majorana neutrino N in pp collisions expected at the CERN LHC collider stemming from the partonic collisions. Owing to the QCD factorization theorem, the hadronic cross section are given in terms of convolution of the partonic cross sections $\hat{\sigma}(\tau s, m^*)$, evaluated at the partons center of mass energy $\sqrt{\hat{s}} = \sqrt{\tau s}$, and the universal parton distribution functions f_i which depend on the parton longitudinal momentum fractions, x , and on the factorization scale \hat{Q} :

$$\sigma = \sum_{ij} \int_{\frac{m_*^2}{s}}^1 d\tau \int_\tau^1 \frac{dx}{x} f_i(x, Q^2) f_j\left(\frac{\tau}{x}, Q^2\right) \hat{\sigma}(\tau s, m^*).$$

For the calculation of the production cross section in proton-proton collisions at LHC, we have used CTEQ6m parton distribution functions [54]. The factorization and renormalization scale has been set to $\hat{Q} = m^*$.

In Fig. 2 (left) we present the cross section against the heavy Neutrino mass for $\Lambda = 10$ TeV for the LHC center of mass energy $\sqrt{s} = 13$ TeV. It is evident that the contact interaction dominates the production of the heavy composite Majorana neutrino by a factor that ranges between two and three orders of magnitude, varying the heavy neutrino mass between 1 and 5 TeV, and for the given choice of the compositeness scale ($\Lambda = 10$ TeV). In Fig. 2 (right) we compare the cross sections of $pp \rightarrow \ell^+ \ell^+ jj$ with the one of $pp \rightarrow \ell^- \ell^- jj$. The cross section for the production of positive di-lepton is larger than that for the production of negative di-leptons as expected in proton-proton collisions due to the larger luminosity of a $u\bar{d}$ pair (needed to produce $\ell^+ \ell^+$) compared to that of a $\bar{u}d$ (needed to produce $\ell^- \ell^-$).

The heavy Majorana neutrino N can decay again through both gauge and contact interactions. The decay amplitudes are related, via appropriate crossing symmetry exchanges, to those describing the single production and depicted in Fig. 1. The possible decays are:

$$N \rightarrow \ell q \bar{q}' \quad N \rightarrow \ell^+ \ell^- \nu(\bar{\nu}) \quad N \rightarrow \nu(\bar{\nu}) q \bar{q}'.$$

In the first we can have a positive lepton, a down-type quark and an up-type antiquark or a negative lepton an up-type quark and a down-type antiquark; in the second owing to the Majorana character of N we can have either a neutrino or an antineutrino of the same flavor of the heavy neutrino N and accordingly two opposite sign leptons belonging to a family that can be the same or different from the other one, or in alternative a positive (negative) lepton of the same family of the heavy neutrino and a negative (positive) lepton and an antineutrino (neutrino) belonging to a family that can be the same or different from the other one; in the third we can have a neutrino or an anti neutrino and a quark and an antiquark both of up-type or both of down-type. In

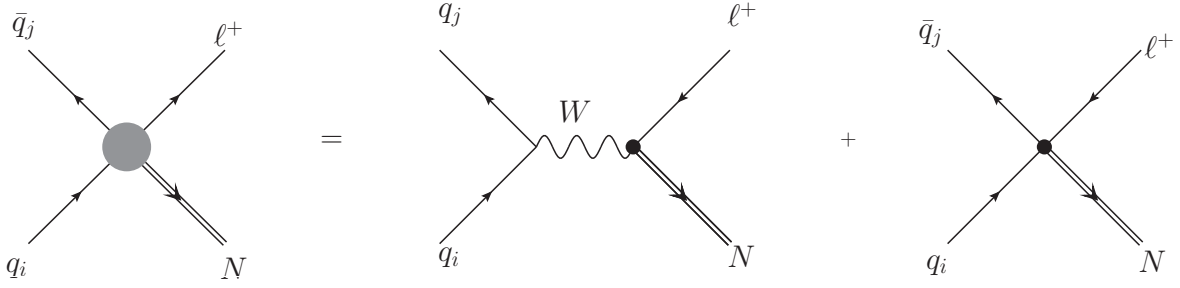


FIG. 1. The dark grey blob describes the production of on shell heavy Majorana neutrinos N in proton-proton collisions at LHC. The production is possible both with gauge interactions (first diagram in the right-hand side) and four fermion contact interactions (second diagram in the right-hand side).

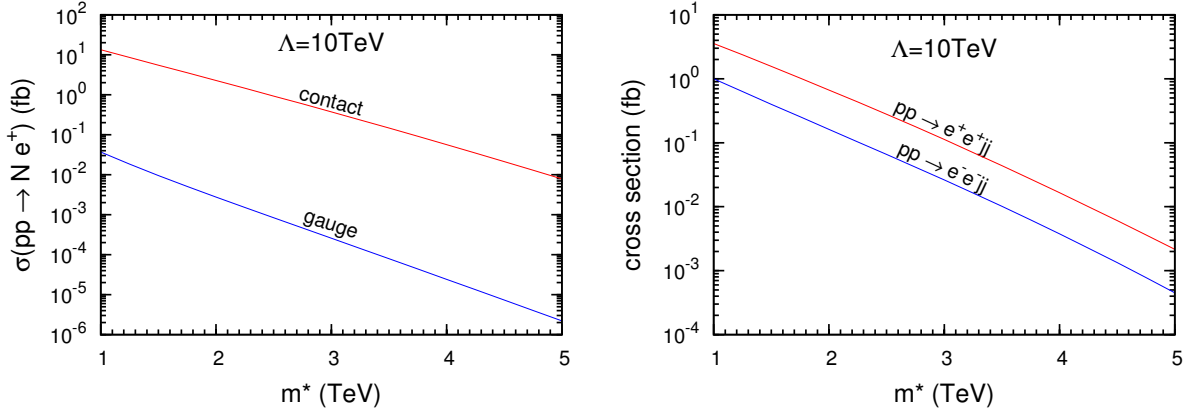


FIG. 2. Left: The production cross section of the process $pp \rightarrow Ne^+$ for gauge and contact interactions at $\sqrt{s} = 13$ TeV. Right: Comparison between cross sections of the final state with negative leptons and of the final state with positive leptons. For the calculation we used CTEQ6m parton distribution functions and we put the factorization (renormalization) scale to $\hat{Q} = m_N = m^*$

Fig. 3 we present the width Γ and the branching ratio \mathcal{B} for $N \rightarrow \ell^+ q \bar{q}'$, the decay that gives the final signature under examination of two like-sign leptons and di-jet, $pp \rightarrow \ell^+ \ell^+ jj$ which is a signature well known to be rather clean (due to the low expected SM background). Relevant yields are ensured by the rather large \mathcal{B} .

This peculiar final state being a lepton number violating process ($\Delta L = +2$) is only possible if the heavy neutrino is of Majorana type. In this work we chose to focus on the specific signature with two positive leptons due to its larger cross section as shown in Fig. 2(right). It is important to remark that the like-sign di-lepton plus di-jet signature can be realized by two distinct classes of Feynman diagrams which are shown in Fig. 4. In Fig. 4(a) there is a t -channel exchange of a virtual heavy Majorana neutrino while in Fig. 4(b) the heavy Neutrino is resonantly produced (s -channel) and its subsequent decay; In Fig. 4, each dark (grey) blob includes both a gauge or a contact interaction term whose Feynman diagrams are those shown in Fig. 1.

The process in Fig. 4(a) is the collider-analogous of the neutrinoless double- β decay ($0\nu\beta\beta$), the well known lepton number violating ($\Delta L = \pm 2$) nuclear rare de-

cay [55, 56] which, if detected, would unambiguously verify the Majorana nature of neutrinos. The half life of the $0\nu\beta\beta$ is currently bounded as $T_{1/2}^{0\nu\beta\beta} \geq 1.1 \times 10^{25}$ yr [57] at 90% confidence level, from the data of the ^{136}Xe EXO (Enriched Xenon Observatory)-200 experiment. Previous searches with ^{76}Ge (the GERDA experiment) [58] and with ^{136}Xe (the KamLAND-Zen experiment) [59] had established a half-life longer than 10^{25} years. In an high energy collider a heavy Majorana neutrino can be produced in resonance, Fig. 4(b), if the mass of the neutrinos is kinematically accessible $m_N < \sqrt{s}$, where \sqrt{s} is the energy in the parton center of mass frame. In this case the cross section for the signature $pp \rightarrow \ell\ell jj$ is approximated by $\sigma(pp \rightarrow \ell\ell jj) \approx \sigma(pp \rightarrow \ell N) \mathcal{B}(N \rightarrow \ell jj)$. The resonant production rate is dominant relative to the virtual neutrino exchange contribution. This was demonstrated in [24] for the gauge-only case and it is still true in the current model including also the contact interactions. This has been explicitly verified and is shown in Fig. 5(b).

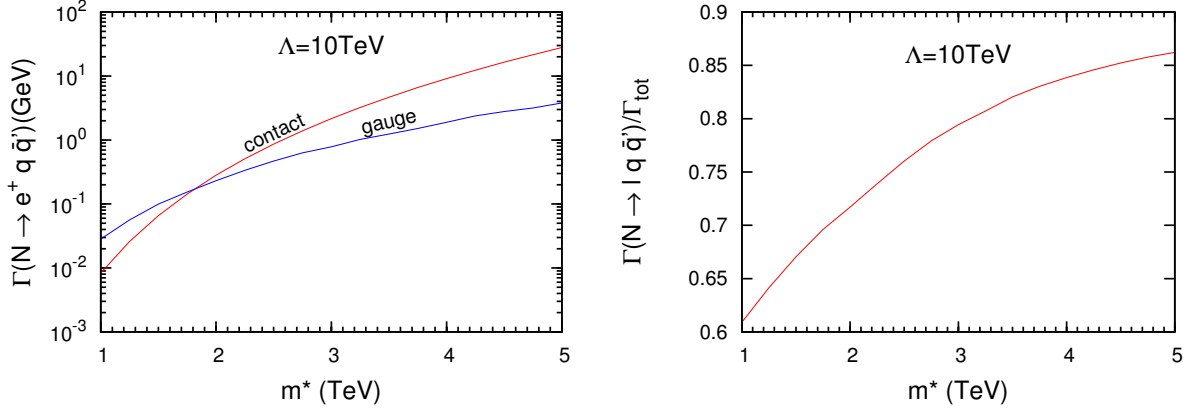


FIG. 3. Left: The gauge and contact contributions to the width of the decay of the heavy neutrino N into a lepton and two quarks $\Gamma(N \rightarrow \ell^+ q \bar{q})$. Right: The branching ratio $\mathcal{B}(N \rightarrow \ell^+ q \bar{q})$ of the same decay.

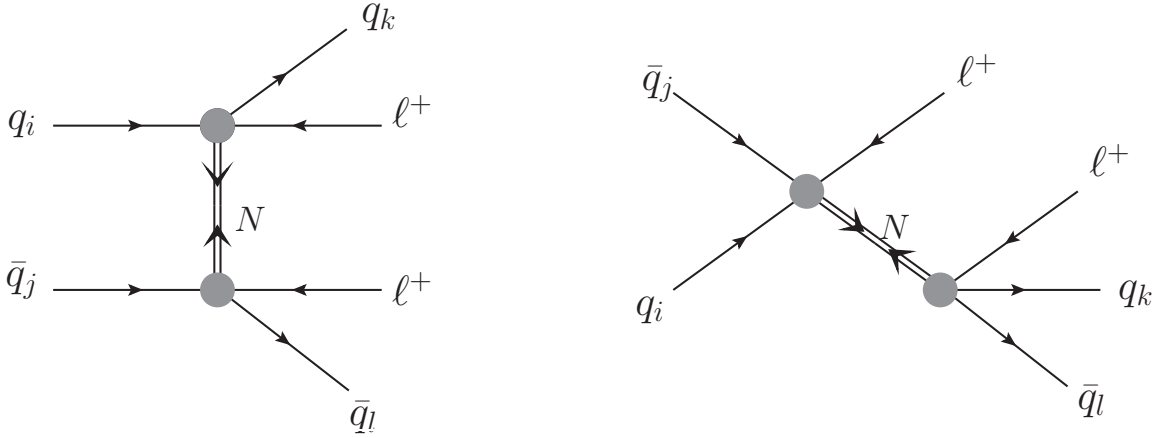


FIG. 4. On the left the process with the virtual heavy composite Majorana neutrino (N), on the right the process with resonant production of N and its subsequent decay. The dark blob includes both gauge and contact interactions (see Fig. 1).

IV. SIGNAL AND BACKGROUND

As it is well known in the standard model the lepton number L is strictly conserved and thus processes like those in Eq. (1) with $\Delta L \pm 2$ are not allowed. However within the SM there are several processes that can produce two same sign leptons in association with jets. The following processes are considered as main backgrounds [25]

$$pp \rightarrow t\bar{t} \rightarrow \ell^+ \ell^+ \nu \nu \text{ jets}, \quad (13a)$$

$$pp \rightarrow W^+ W^+ W^- \rightarrow \ell^+ \nu \ell^+ \nu jj. \quad (13b)$$

We discuss here the main kinematic differences between the signal and the background to choose suitable cuts for optimizing the signal/background ratio. From the point of view of the leptons' transverse momentum distributions in Fig. 6 (top-left and center-left), signal and background are very well separated, for the given values of the parameters ($m^* = 1000$ GeV and $\Lambda = 10$ TeV) and we can reduce drastically the background applying a

cut on the transverse momentum of the leading positron at 200 GeV and a cut in the transverse momentum of the second-leading positron at 100 GeV:

$$p_T(e_{\text{leading}}^+) \geq 200 \text{ GeV}, \quad (14a)$$

$$p_T(e_{\text{second-leading}}^+) \geq 100 \text{ GeV}. \quad (14b)$$

On the contrary we can see from Fig. 6 (top-right and center-right) that the angular distributions of the leading and second-leading leptons are quite similar between signal and background.

From Fig. 6 (bottom-left) regarding the signal we can see that a large fraction of the events have the two jets with a very small separation in the (η, ϕ) plane, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, (η is the pseudorapidity and ϕ the azimuthal angle in the transverse plane). The corresponding ΔR distribution is peaked at $(\Delta R)_{\text{min}} = 0.4$. Therefore, in the reconstruction process, we are likely to have merging, i.e. the two jets can be often reconstructed as a single jet.

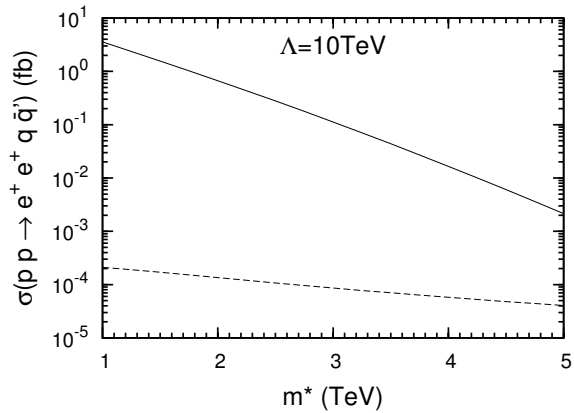


FIG. 5. Comparison between the parton-level cross sections of the process with resonant production of heavy Majorana neutrino (solid line) and that with a virtual heavy Majorana neutrino (dashed line). Both gauge and contact interactions are considered in each case.

Let us also remark the fact that information about the mass of the heavy Majorana neutrino can be obtained from the invariant mass distribution of the second-leading lepton and the two jets. Indeed in Fig. 6 (bottom-right) we show that this distribution has a very sharp peak in correspondence of the heavy Majorana neutrino mass. This is indeed expected since in the resonant production the heavy Majorana neutrino N is decaying to $\ell^+ jj$ and the lepton from N is expected to be the second-leading, while the leading lepton is the one produced in association with N , in $pp \rightarrow \ell^+ N$.

Finally we show explicitly that the di-lepton plus di-jet signature from a heavy composite Majorana neutrino can easily explain the excess observed by the CMS collaboration [3] in the $eejj$ invariant mass distribution in the interval $1.8 \text{ TeV} < M_{eejj} < 2.2 \text{ TeV}$. Fig. 7 shows, at generator level and for a particular point of the parameter space ($\Lambda = 10 \text{ TeV}$, $m^* = 1000 \text{ GeV}$), that the $eejj$ invariant mass distribution can easily accommodate an excess in the interval where it has been claimed by the CMS collaboration. The fact that the excess is observed in the electron channel but not in the muon channel could be explained in our model simply by invoking a rather natural mass splitting between the excited electron (e^*) and muon (μ^*) instead of assuming that $m_{e^*} \approx m_{\mu^*} \approx m^*$.

V. FAST DETECTOR SIMULATION AND RECONSTRUCTED OBJECTS

In order to take into account the detector effects, such as efficiency and resolution in reconstructing kinematic variables, we interface the LHE output of CalcHEP with the software DELPHES that simulates the response of a generic detector according to predefined configurations. We use a CMS-like parametrization. For the signal we consider a scan of the parameter space (Λ , m^*) within

the ranges $\Lambda \in [8, 40] \text{ TeV}$ with step of red 1 TeV and $m^* \in [500, 5000] \text{ GeV}$ with step of 250 GeV. For each signal point and each background we generate 10^5 events in order to have enough statistics to evaluate the reconstruction efficiencies (ϵ_s , ϵ_b) of the detector and of the cuts previously fixed (see Eq. 14a, 14b). Then we select the events with two positive electrons, while, although our final state has two jets, we do not require the presence of two jets because, as shown in the previous section, we have merging in a great fraction of the events. Once we have the number of the selected events we evaluate the reconstruction efficiencies, then for a given luminosity L it is possible to estimate the expected number of events for the signal (N_s) and for the background (N_b) and finally the statistical significance (S):

$$N_s = L\sigma_s\epsilon_s, \quad N_b = L\sigma_b\epsilon_b, \quad S = \frac{N_s}{\sqrt{N_b}}. \quad (15)$$

In Fig. 8 Top-left, Top-right and Bottom-left we show the contour plots of $S = 3$ and $S = 5$ in the parameter space (Λ , m^*) for three different values of integrated luminosity $L = 30, 300, 3000 \text{ fb}^{-1}$. The regions below the curves are excluded. The colored filled bands are an estimate of the statistical error. In Fig. 8 Bottom-right we compare the 5-sigma curves at the three integrated luminosity values.

Finally in Fig. 9 we compare our 3- σ contour plots ($S = 3$) for the three different values of integrated luminosity $L = 30, 300, 3000 \text{ fb}^{-1}$ of Fig. 8 with the 95% confidence level exclusion bounds from two Run I analyses at $\sqrt{s} = 8 \text{ TeV}$: ATLAS with 13 fb^{-1} [32] and CMS with 19.7 fb^{-1} [33]. The shaded regions below the solid, dashed and dot-dashed lines are the current CMS exclusion at $\sqrt{s} = 8 \text{ TeV}$ with 19.7 fb^{-1} of integrated luminosity (blue) [33] and the ATLAS exclusion at $\sqrt{s} = 8 \text{ TeV}$ with 13 fb^{-1} (yellow) and the region of the parameters where the model is not applicable (grey) i.e. $m^* > \Lambda$. Such experimental exclusion regions from Run I are compared with the contour plots expected from Run II, considering the process studied in this work. The solid (magenta), dashed (red) and dot-dashed (green) –without shading– are the projected contour maps for $S = 3$ (3- σ) in the parameter space (Λ , m^*) of the statistical significance for $\sqrt{s} = 13 \text{ TeV}$ and for the following three values of the integrated luminosity $L = 30, 300, 3000 \text{ fb}^{-1}$.

The great potential of discovery or improving the current model limits of the $eejj$ signature from a heavy composite majorana neutrino as function of the increasing integrated luminosity is clearly evident and is the authors' opinion that a dedicated experimental analysis of this channel should be undertaken within RunII of the LHC.

VI. DISCUSSION AND CONCLUSIONS

We have performed a phenomenological study of the production of heavy composite Majorana neutrinos at

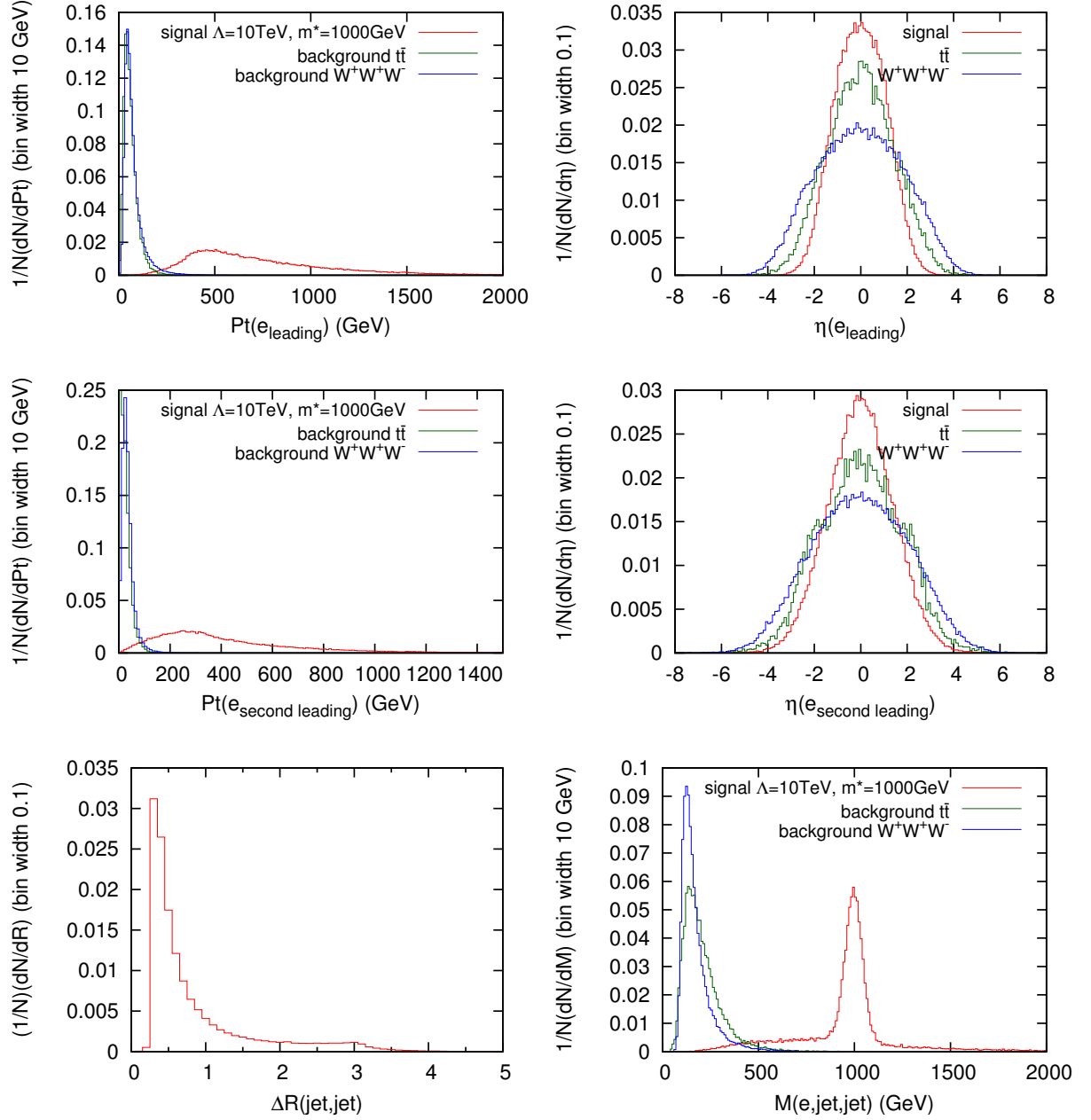


FIG. 6. Top-left: The leading positron transverse momentum distribution. Top-right: The leading positron pseudorapidity distribution. Center-left: The second-leading positron transverse momentum distribution. Center-right: The second-leading positron pseudorapidity distribution. Bottom-left: The distribution in the ΔR of the two jets. Bottom-right: The distribution in the invariant mass of the second-leading positron and the two jets.

LHC in view of the recent observation by the CMS Collaboration of a $2.5\text{-}\sigma$ excess in the $eejj$ channel. We take up the well known composite model scenario with heavy excited fermions (quarks and leptons). These states have been searched for in a number of dedicated direct searches. In this study we reconsider the hypothesis that the excited neutrino is of Majorana type. This hypothesis had been considered in [22] where a model based only on gauge interactions was used to describe the production rates and decay of the composite Majorana

neutrino. However a composite model scenario quite generically predicts, in addition to the presence of excited states, also four fermion contact interactions. We have included the contribution of contact interactions in the phenomenology of the excited Majorana neutrino, hitherto not considered in the literature. The model is implemented in CalcHEP which allows quite extensive simulations at the generator level. The contact interaction mechanism turns out to be dominant in the resonant production of the heavy Majorana neutrino. We have per-

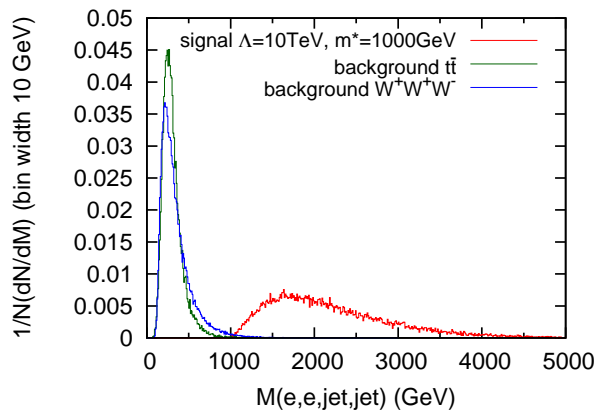


FIG. 7. (Color Online) Invariant mass distribution of the $eejj$ system at $\sqrt{s} = 13$ TeV. The signal distribution gives clearly an excess relative to the standard model expectation in the region of large invariant masses.

formed a kinematic study of the same-signed di-lepton plus di-jet signature analyzing in detail both signal and background in order to optimize the signal over background ratio.

We find that the invariant mass distribution of the system made up by the second-leading lepton and the two jets is highly correlated to the heavy Majorana neutrino mass, see Fig. 6 (bottom-right). A fast simulation of the detector effects and efficiencies in the reconstruction process is performed using the DELPHES [38] package based on a CMS-like configuration.

We scanned the two dimensional parameter space (m^*, Λ) for some benchmark values and computed the statistical significance. We provide the contour plots of the statistical significance S at 3- and 5-sigma (see Fig. 8). We find for instance that with $\Lambda = 15$ TeV the LHC can reach a 3-sigma sensitivity for masses up to $m^* = 1500, 2500, 3000$ GeV respectively for an integrated luminosity of $L = 30, 300, 3000$ fb $^{-1}$.

Finally we compared (see Fig. 9) such expected exclusion bounds in the parameter space (m^*, Λ) with the experimental data of Run I c.f. [32, 33]. Such analyses have investigated signatures of excited electrons and muons ($\ell = e^*, \mu^*$) being produced by contact interactions ($pp \rightarrow \ell\ell^*$) and decaying via $\ell^* \rightarrow \ell + \gamma$. Strictly speaking such analyses access the parameters spaces (m_{e^*}, Λ) and (m_{μ^*}, Λ) that are in principle different from the one presented here (m_N, Λ) . However all excited states masses can be assumed to be approximately degenerate, at least at a first order approximation. Under this hypothesis $M_N \approx m_{e^*} \approx m_{\mu^*} \approx m^*$ the $eejj$ signature discussed in this work provides contour maps that can be considered on the same parameter space of the other analyses based on $pp \rightarrow \ell\ell\gamma$ [32, 33]. This comparison shows that the $eejj$ signature from a heavy composite Majorana neutrino has the potential to improve sensibly the current constraints on the composite scenario.

Before concluding we would like to comment briefly

about another anomaly reported by the ATLAS Collaboration and on recent results from ATLAS and CMS Collaborations from RunII, and how our model could interpret them.

In a search [60] for high-mass di-boson resonances with boson-tagged jets at $\sqrt{s} = 8$ TeV the ATLAS Collaboration has reported an excess at around 2 TeV with a global significance of 2.5 standard deviations (note however that the same search performed by the CMS Collaboration did not observe a similar excess [61]). Our model contains fermion resonances (excited quarks and leptons) which do not couple directly to a pair of gauge bosons. Indeed a fermion cannot decay to a pair of gauge bosons by angular momentum conservation. On general grounds our fermion resonances could produce final states with a pair of gauge bosons but these would always be accompanied by other objects such as leptons and jets (SM fermions). As an example one might think to pair produce the excited neutrinos $pp \rightarrow Z^* \rightarrow \nu^* \bar{\nu}^*$ with the excited neutrinos decaying leptonically $\nu^* \rightarrow W^\pm e^\mp$. One obtains a final signature of $W^+W^-e^+e^-$ which is different from the one considered in the ATLAS search for high mass di-boson resonances consisting of only gauge boson pairs (WW, WZ or ZZ).

However one might imagine to pair produce the charged excited fermions, for instance e^* and/or q^* , almost at threshold (if they are very massive). Such pair of heavy fermions could in principle form a 1S bound state (via the known Coulomb and/or color interaction) which in turn could decay to a pair of intermediate vector boson given the high mass of the hypothetical heavy fermions [62, 63].

Therefore our model has *in principle* the potential to reproduce an excess in the di-boson signal. The estimate of such effects is certainly very interesting and it would surely be worth further investigation (one needs for instance to understand whether such bound states could form at all in the first place). However a quantitative analysis goes beyond the purview of the present work and we postpone it to a future study.

Very recently the CMS and ATLAS Collaborations have released the first results of Run II of the LHC at $\sqrt{s} = 13$ TeV, with respectively 42 pb $^{-1}$ and 80 pb $^{-1}$ of integrated luminosity [64, 65], reporting about a search for hadronic resonances in the di-jet channel and showing \approx 1-sigma excess(es) at an invariant mass of about 5 TeV in the measured di-jet invariant mass distribution.

Such excess(es), if confirmed by further data and statistics, could in principle signal the first hadronic (excited quark) resonance level in a composite model scenario beyond the 2 TeV $eejj$ anomaly. Indeed the analysis in [64] excludes excited quarks masses from around 3 TeV at 95% C.L (if $m^* = \Lambda$) while in [33] excited lepton masses are excluded at 95% C.L. from $m^* = 2.5$ TeV (again assuming $m^* = \Lambda$). These experimental bounds would seem to preclude the possibility of an excited fermion bound state with regard to the explanation of the di-boson anomaly at 2 TeV (see above) since a

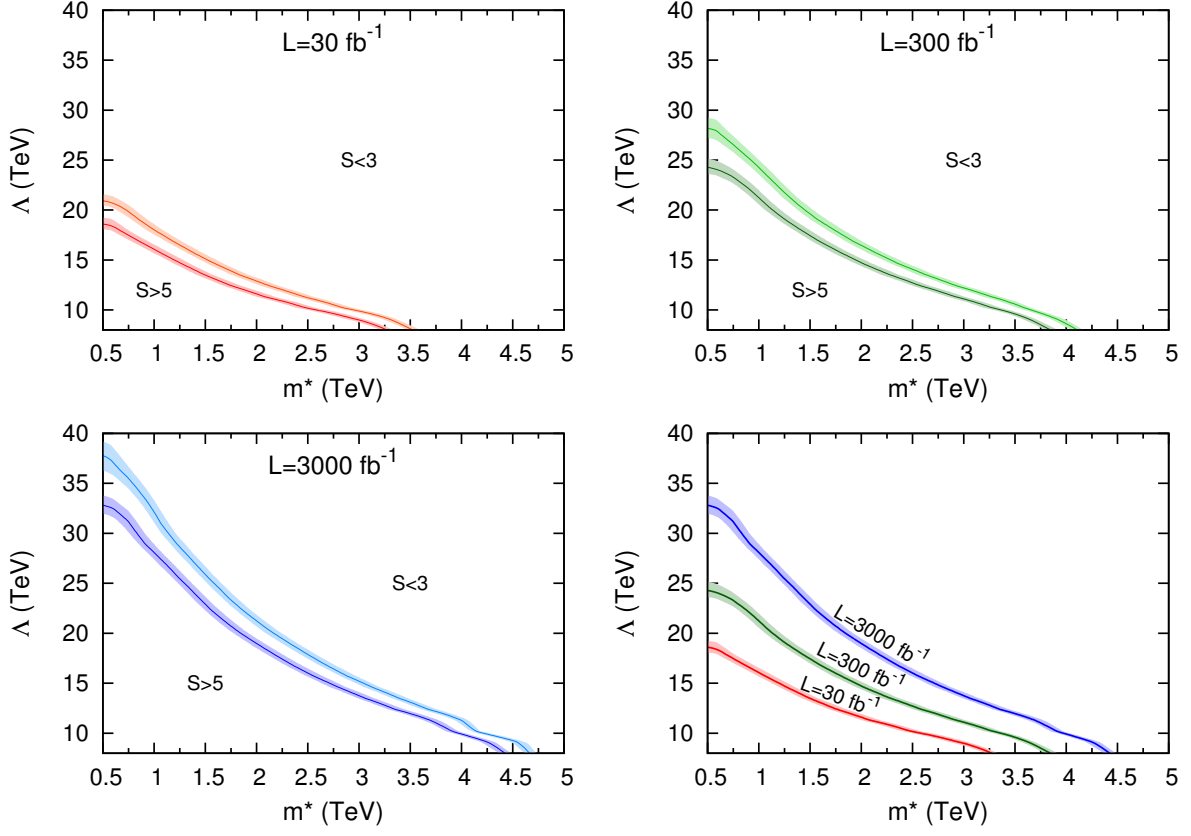


FIG. 8. (Color Online) Contour maps of the statistical significance for $S = 5$ and $S = 3$ in the parameter space (Λ, m^*) for $\sqrt{s} = 13$ TeV and for three values of the integrated luminosity $L = 30, 300, 3000 \text{ fb}^{-1}$. The solid lines are the central values, the dashed lines are the extremes of the errors band. In the lower right panel we compare the 5-sigma exclusion plots at three values of integrated luminosity. Regions below the curves are excluded.

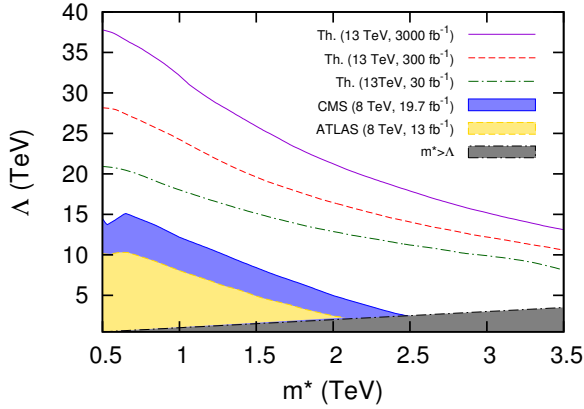


FIG. 9. (Color Online) Current bounds on the plane of parameters (Λ, m^*) from CMS and ATLAS searches of $pp \rightarrow \ell\ell^* \rightarrow \ell\ell\gamma$ (Run I) versus the expected exclusion curves at Run II from the heavy Majorana neutrino signature ($pp \rightarrow \ell N \rightarrow \ell\ell jj$). See text for further details.

q^* (e^*) bound state would need to have to a mass of at least 6 TeV (5 TeV). However the quoted bounds for the

excited fermions are for $m^* = \Lambda$ which is the limit of validity of the effective composite model. For values of Λ higher than m^* the actual bounds on m^* are lower (see for example Fig. 9). In such regions of the parameter space the 2 TeV di-boson anomaly could still be explained (in principle) by a $q^*\bar{q}^*$ (or $e^*\bar{e}^*$) bound state with a mass $m^* \approx 1$ TeV.

As a last remark concerning the $eejj$ anomaly we would like to comment on the fact that (i) the same excess is not observed in the $\mu\mu jj$ channel and (ii) the observed charge asymmetry of the like sign di-leptons [3]. The absence of the excess in the $\mu\mu jj$ channel could be explained by our model simply assuming that the excited muon state (μ^*) is somewhat heavier than the e^* and so it would be observable only at higher energies. The observed $eejj$ excess consists indeed of 14 events of which 13 are opposite sign (OS) and only one is same sign (SS). It must be said that our Mirror type composite model with one Majorana neutrino will produce the same yield of OS and SS events. Such feature could be explained within our composite model assuming the existence of an additional Majorana ν^* state with a slightly different mass. Indeed it has been shown, albeit within a different (seesaw) model [8, 9], that the interference between

the contributions of two different Majorana states could depress the SS yield relative to the OS. The interference effect could also explain the absence of a peak in the observed invariant mass distribution of the second leading electron and the two jets (see our Fig. 6 –bottom right–). In view of this it could be worthwhile either to upgrade the CalcHEP implementation of our Mirror model to include other Majorana states or alternatively to reconsider the homo-doublet model with $\nu_L^*-\nu_R^*$ mixing. In order to address quantitatively this issue we would need to build a new model (with more than one Majorana neutrino state) in the CalcHEP generator. This goes beyond the scope of the present work and will be addressed in a future study.

In summary the results presented in this work are quite encouraging and certainly endorse the interest and feasibility of a full fledged analysis of the experimental data of the upcoming LHC Run II for a search of the heavy com-

posite Majorana neutrino, within a Mirror type model, in proton proton collisions at $\sqrt{s} = 13$ TeV.

ACKNOWLEDGMENTS

The authors acknowledge constant and encouraging support from the CMS group, University of Perugia, Department of Physics and Geology and INFN, Sezione di Perugia.

-
- [1] G. Aad *et al.*, *Physics Letters B* **710**, 49 (2012).
 - [2] S. Chatrchyan *et al.*, *Physics Letters B* **710**, 26 (2012).
 - [3] V. Khachatryan *et al.* (CMS Collaboration), *Eur.Phys.J. C* **74**, 3149 (2014), [arXiv:1407.3683 \[hep-ex\]](#).
 - [4] *Search for Pair-production of First Generation Scalar Leptoquarks in pp Collisions at $\sqrt{s} = 8$ TeV*, Tech. Rep. CMS-PAS-EXO-12-041 (CERN, Geneva, 2014); V. Khachatryan *et al.* (CMS Collaboration), (2015), [arXiv:1509.03744 \[hep-ex\]](#).
 - [5] M. Heikinheimo, M. Raidal, and C. Spethmann, *Eur.Phys.J. C* **74**, 3107 (2014), [arXiv:1407.6908 \[hep-ph\]](#).
 - [6] F. F. Deppisch, T. E. Gonzalo, S. Patra, N. Sahu, and U. Sarkar, *Phys.Rev. D* **91**, 015018 (2015), [arXiv:1410.6427 \[hep-ph\]](#).
 - [7] J. Aguilar-Saavedra and F. Joaquim, *Phys.Rev. D* **90**, 115010 (2014), [arXiv:1408.2456 \[hep-ph\]](#).
 - [8] P. S. B. Dev and R. N. Mohapatra, *Phys. Rev. Lett.* **115**, 181803 (2015).
 - [9] R. L. Awasthi, P. S. B. Dev, and M. Mitra, (2015), [arXiv:1509.05387 \[hep-ph\]](#).
 - [10] F. F. Deppisch, L. Graf, S. Kulkarni, S. Patra, W. Rodejohann, N. Sahu, and U. Sarkar, (2015), [arXiv:1508.05940 \[hep-ph\]](#).
 - [11] B. A. Dobrescu and A. Martin, *Phys.Rev. D* **91**, 035019 (2015), [arXiv:1408.1082 \[hep-ph\]](#).
 - [12] B. Allanach, S. Biswas, S. Mondal, and M. Mitra, *Phys.Rev. D* **91**, 011702 (2015), [arXiv:1408.5439 \[hep-ph\]](#).
 - [13] B. Allanach, S. Biswas, S. Mondal, and M. Mitra, *Phys.Rev. D* **91**, 015011 (2015), [arXiv:1410.5947 \[hep-ph\]](#).
 - [14] S. Biswas, D. Chowdhury, S. Han, and S. J. Lee, *JHEP* **1502**, 142 (2015), [arXiv:1409.0882 \[hep-ph\]](#).
 - [15] F. S. Queiroz, K. Sinha, and A. Strumia, *Phys.Rev. D* **91**, 035006 (2015), [arXiv:1409.6301 \[hep-ph\]](#).
 - [16] B. Allanach, A. Alves, F. S. Queiroz, K. Sinha, and A. Strumia, (2015), [arXiv:1501.03494 \[hep-ph\]](#).
 - [17] M. Dhuria, C. Hati, R. Rangarajan, and U. Sarkar, (2015), [arXiv:1501.04815 \[hep-ph\]](#).
 - [18] J. Gluza and T. Jeliński, *Physics Letters B* **748**, 125 (2015).
 - [19] W.-Y. Keung and G. Senjanović, *Phys. Rev. Lett.* **50**, 1427 (1983).
 - [20] A. Datta, M. Guchait, and D. P. Roy, *Phys. Rev. D* **47**, 961 (1993).
 - [21] A. Datta, M. Guchait, and A. Pilaftsis, *Phys. Rev. D* **50**, 3195 (1994).
 - [22] O. Panella, C. Carimalo, and Y. N. Srivastava, *Phys. Rev. D* **62**, 015013 (2000).
 - [23] F. M. L. Almeida, Y. A. Coutinho, J. A. M. Simões, and M. A. B. d. Vale, *Phys. Rev. D* **62**, 075004 (2000).
 - [24] O. Panella, M. Cannoni, C. Carimalo, and Y. Srivastava, *Phys.Rev. D* **65**, 035005 (2002).
 - [25] T. Han and B. Zhang, *Phys. Rev. Lett.* **97**, 171804 (2006).
 - [26] A. Atre, T. Han, S. Pascoli, and B. Zhang, *Journal of High Energy Physics* **2009**, 030 (2009).
 - [27] P. S. B. Dev, A. Pilaftsis, and U.-k. Yang, *Phys. Rev. Lett.* **112**, 081801 (2014).
 - [28] F. F. Deppisch, P. S. B. Dev, and A. Pilaftsis, *New Journal of Physics* **17**, 075019 (2015).
 - [29] A. Das and N. Okada, *Phys. Rev. D* **88**, 113001 (2013).
 - [30] A. Das, P. B. Dev, and N. Okada, *Physics Letters B* **735**, 364 (2014).
 - [31] A. Das and N. Okada, (2015), [arXiv:1510.04790 \[hep-ph\]](#).
 - [32] G. Aad and L. Zwalinski, *New Journal of Physics* **15**, 093011 (2013).
 - [33] (CMS Collaboration) CMS-PAS-EXO-14-015 (2015).
 - [34] M. Peskin, “International Symposium on Lepton Photon Interactions at High Energies,” (1985).
 - [35] R. Leonardi, O. Panella, and L. Fanò, *Phys. Rev. D* **90**, 035001 (2014).
 - [36] A. Pukhov, E. Boos, M. Dubinin, V. Edneral, V. Ilyin, D. Kovalenko, A. Kryukov, V. Savrin, S. Shichanin, and A. Semenov, [arXiv:hep-ph/9908288v2](#).
 - [37] A. Belyaev, N. D. Christensen, and A. Pukhov, *Computer Physics Communications* **184**, 1729 (2013).
 - [38] J. de Favereau *et al.* (DELPHES 3), *JHEP* **1402**, 057 (2014), [arXiv:1307.6346 \[hep-ex\]](#).
 - [39] H. Terazawa, K. Akama, and Y. Chikashige, *Phys.Rev. D* **15**, 480 (1977).

- [40] H. Terazawa, *Phys.Rev.* **D22**, 184 (1980).
- [41] E. Eichten, K. D. Lane, and M. E. Peskin, *Phys.Rev.Lett.* **50**, 811 (1983).
- [42] N. Cabibbo, L. Maiani, and Y. Srivastava, *Phys. Lett.* **B139**, 459 (1984).
- [43] U. Baur, M. Spira, and P. Zerwas, *Phys. Rev.* **D42**, 815 (1990).
- [44] C. Giunti and C. W. Kim, *Fundamentals of Neutrino Physics and Astrophysics* (Oxford University Press, Oxford, UK, 2007) pp. 1–728.
- [45] E. Takasugi, *Double beta decay and related topics. Proceedings, International Workshop, Trento, Italy, April 24-May 5, 1995*, *Prog. Theor. Phys.* **94**, 1097 (1995), [arXiv:hep-ph/9506379 \[hep-ph\]](#).
- [46] K. Olive *et al.* (Particle Data Group), *Chin.Phys.* **C38**, 090001 (2014).
- [47] S. Chakdar, K. Ghosh, V. Hoang, P. Q. Hung, and S. Nandi, (2015), [arXiv:1508.07318 \[hep-ph\]](#).
- [48] G. Pancheri and Y. Srivastava, *Phys.Lett.* **B146**, 87 (1984).
- [49] S. Biondini, O. Panella, G. Pancheri, Y. Srivastava, and L. Fanò, *Phys. Rev. D* **85**, 095018 (2012), [arXiv:1201.3764 \[hep-ph\]](#).
- [50] N. D. Christensen and C. Duhr, *Comput.Phys.Commun.* **180**, 1614 (2009), [arXiv:0806.4194 \[hep-ph\]](#).
- [51] “Mathematica,” (Wolfram Research, Inc., Champaign, IL, 2008), version 7.0.
- [52] S. Antusch and O. Fischer, *Journal of High Energy Physics* **2014**, 94 (2014), [10.1007/JHEP10\(2014\)094](#).
- [53] L. Basso, O. Fischer, and J. J. van der Bij, *EPL (Europhysics Letters)* **105**, 11001 (2014).
- [54] J. Pumplin, D. Stump, J. Huston, H. Lai, P. M. Nadolsky, *et al.*, *JHEP* **0207**, 012 (2002), [arXiv:hep-ph/0201195 \[hep-ph\]](#).
- [55] M. Doi, T. Kotani, and E. Takasugi, *Progress of Theoretical Physics Supplement* **83**, 1 (1985).
- [56] F. T. Avignone, S. R. Elliott, and J. Engel, *Rev. Mod. Phys.* **80**, 481 (2008).
- [57] J. Albert *et al.* (EXO-200), *Nature* **510**, 229 (2014), [arXiv:1402.6956 \[nucl-ex\]](#).
- [58] M. Agostini *et al.* (GERDA Collaboration), *Phys. Rev. Lett.* **111**, 122503 (2013).
- [59] A. Gando *et al.* (KamLAND-Zen Collaboration), *Phys. Rev. Lett.* **110**, 062502 (2013).
- [60] G. Aad *et al.* (ATLAS), (2015), [arXiv:1506.00962 \[hep-ex\]](#).
- [61] V. Khachatryan *et al.*, *Journal of High Energy Physics* **08**, 173 (2014), [10.1007/JHEP08\(2014\)173](#).
- [62] N. Fabiano and O. Panella, *Phys. Rev. D* **72**, 015005 (2005).
- [63] N. Fabiano and O. Panella, *Phys. Rev. D* **81**, 115001 (2010).
- [64] *Search for Narrow Resonances using the Dijet Mass Spectrum with 40 pb⁻¹ of pp Collisions at $\sqrt{s} = 13$ TeV*, Tech. Rep. CMS-PAS-EXO-15-001 (CERN, Geneva, 2015).
- [65] *Search for New Phenomena in Dijet Mass and Angular Distributions with the ATLAS Detector at $\sqrt{s} = 13$ TeV*, Tech. Rep. ATLAS-CONF-2015-042 (CERN, Geneva, 2015).